DEEP UNDERGROUND NEUTRINO EXPERIMENT
Status and prospectives

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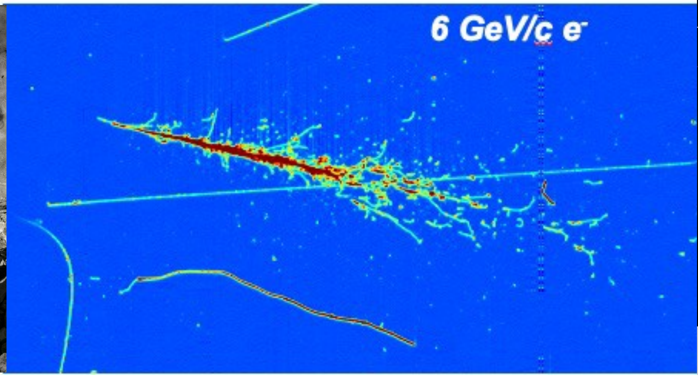
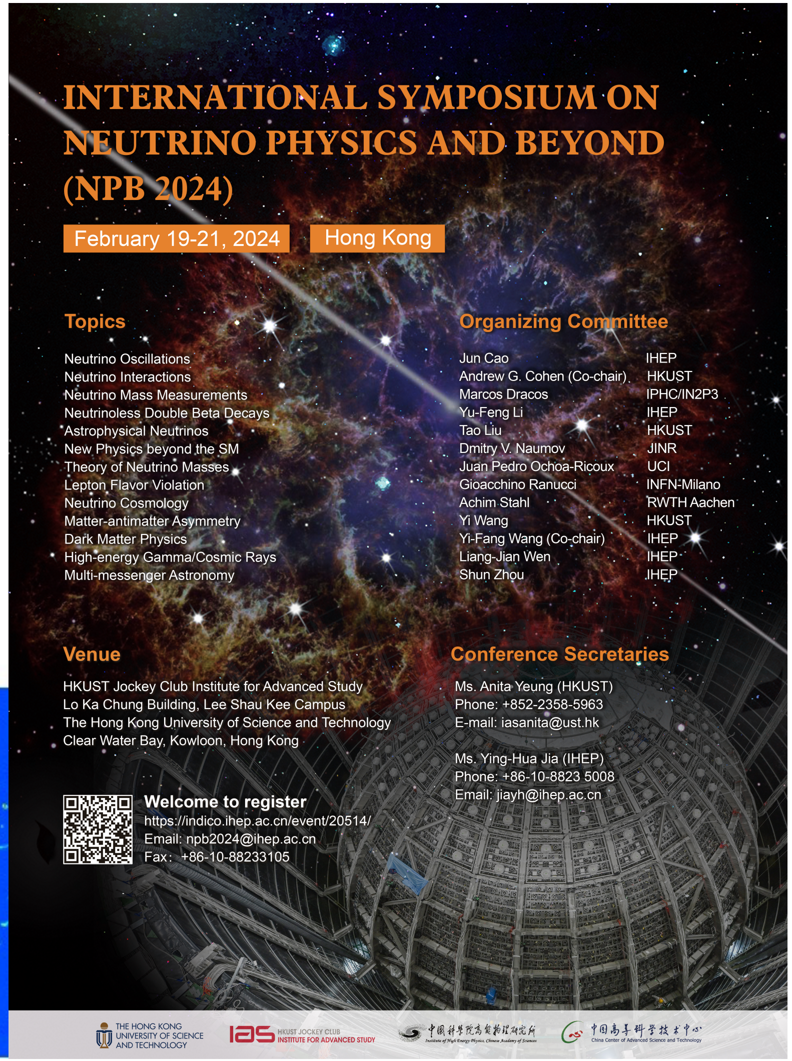
On behalf of the DUNE Collaboration

International Symposium on Neutrino Physics and Beyond 2024
Hong Kong - Feb. 19th - 21st, 2024





Talk outline

- Snapshot on **where we are** on neutrinos
- The **LBNF/PIP-II** projects and the **DUNE** experiment
- The **neutrino beam**
- Status of **LBNF**/**DUNE**
  - Far site **excavations**
  - **Far** detectors and **prototyping at CERN**
  - **Near** site design and **detectors**
- Experimental strategy and DUNE science reach

State of the art in neutrino physics

- The 3 mixed massive-ν paradigm has been quite successful (modulo a few not understood "anomalies")
  - However, knowledge and understanding of neutrino sector is far from being complete:

PDG

$$|\Delta m^2| = 2.49 \pm 0.04\ 10^{-3}\ eV^2 \quad [1.4\%] \qquad \delta m^2 = 7.73 \pm 0.18\ 10^{-5}\ eV^2 \quad [2.2\%]$$

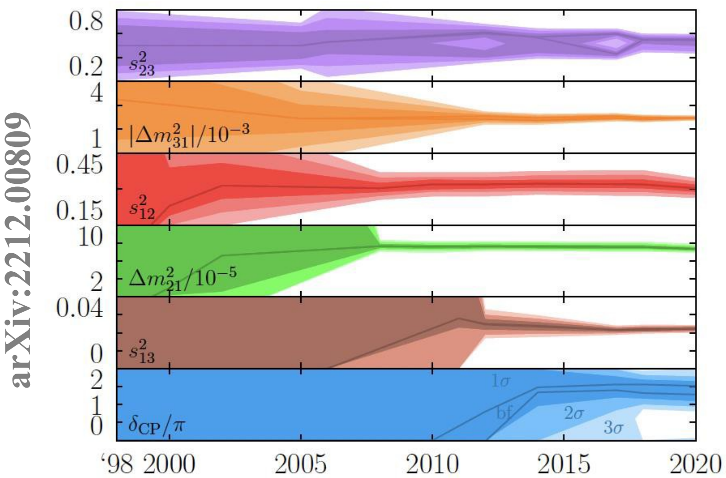
$$\sin^2(\theta_{23}) = 0.54 \pm 0.2 \quad [5\%] \qquad \sin^2(\theta_{13}) = 2.20 \pm 0.07\ 10^{-2} \quad [3.2\%] \qquad \sin^2(\theta_{12}) = 0.307 \pm 0.013 \quad [4\%]$$

UNKNOWN

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta_D} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta_D} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_1} & 0 \\ 0 & 0 & e^{i\alpha_2} \end{pmatrix}$$

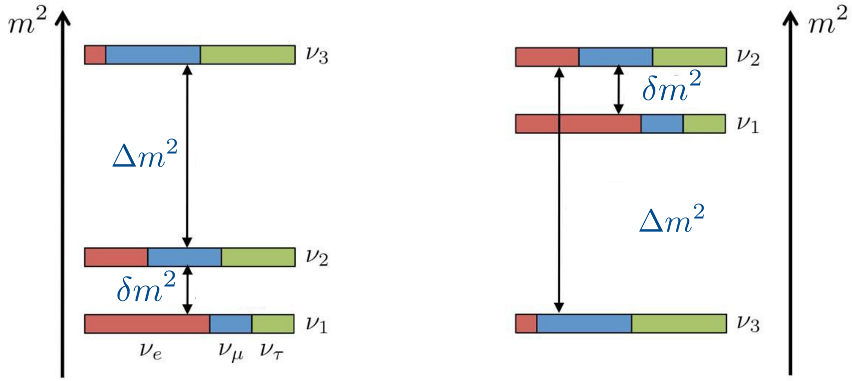
Majorana phases not relevant for oscillations

PROGRESS SINCE 1998 SK DISCOVERY

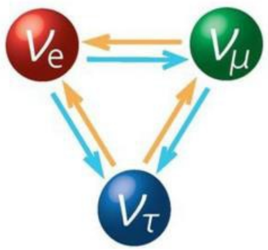


Normal Ordering

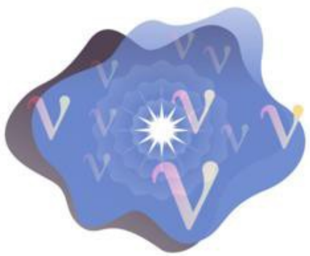
Inverted Ordering



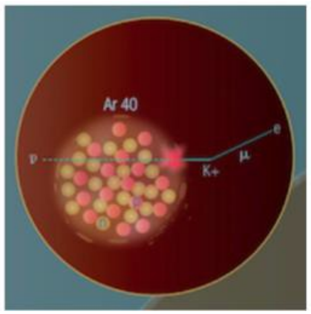
DUNE and its Physics Program in one slide



- **Long- baseline wide-band neutrino beam**
  - Measurement of CP violation phase and determination of the neutrino mass ordering in a single experiment using spectral information
- **Underground location → access to astrophysical neutrinos**
  - Supernova neutrino burst detection – sensitive to the ν_e component
  - Atmospheric neutrino – capability of ν_τ identification
  - Solar neutrinos – potential for detection of hep flux

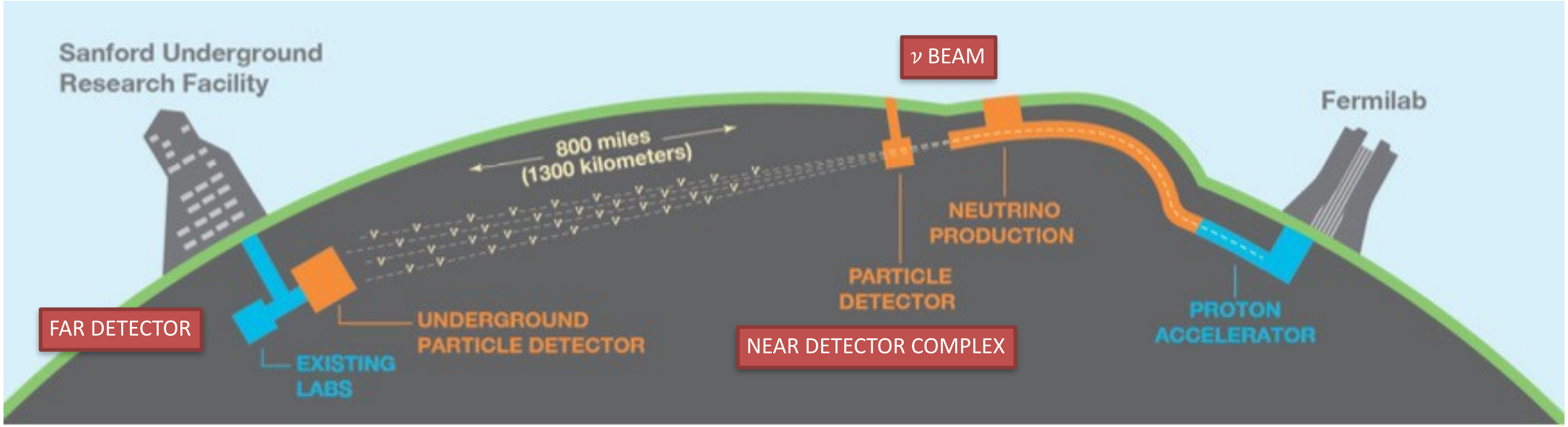


- **Massive detectors with tracking and calorimetric information**
  - Search for baryon number violating processes – p → ν K+, n $\bar{n}$
- **Long baseline + higher energy neutrino beam**
  - ν_τ appearance, NSI searches
- **Capable Near Detector Complex**
  - Precise neutrino physics (cross sections, nuclear effects)
  - BSM searches

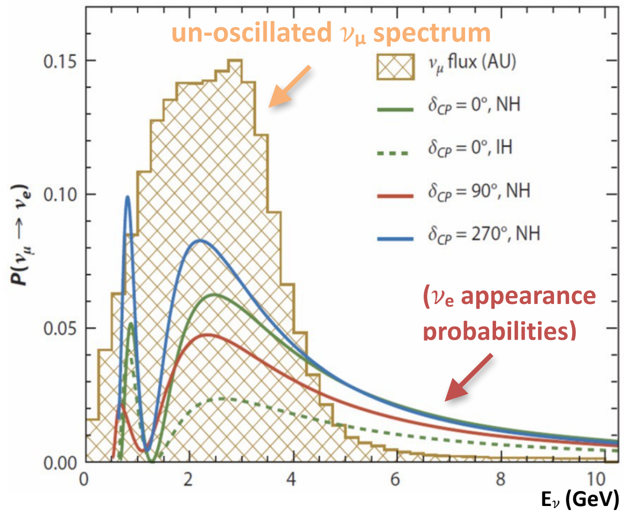


arXiv 1807.10334

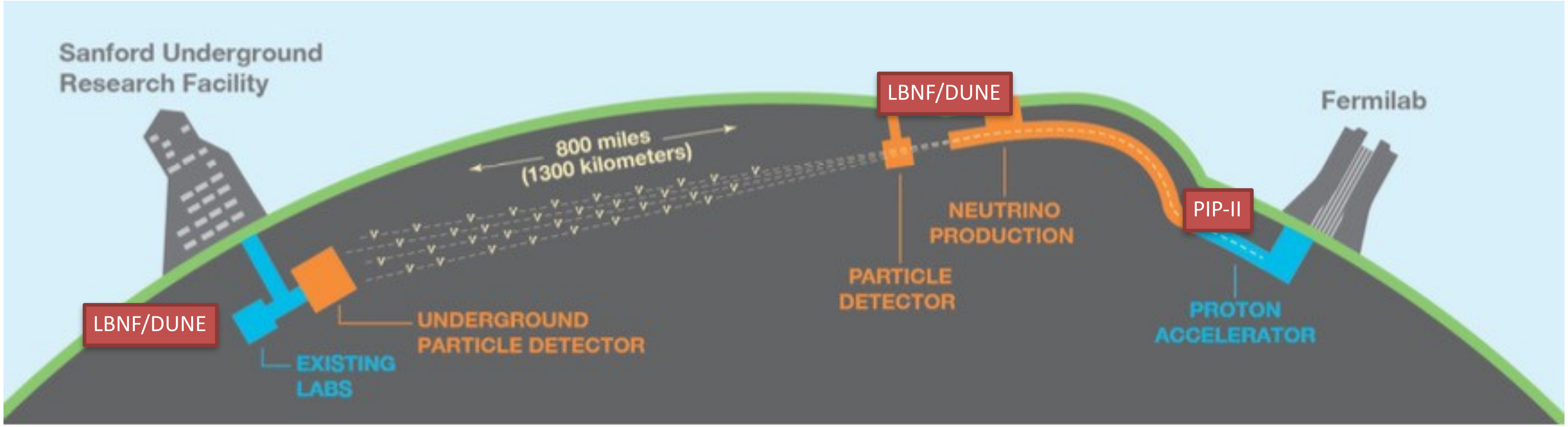
DUNE: the ultimate proton-driven long-baseline experiment



- High precision measurements of ν mixing in a **single experiment.**
- Determination of the ν **mass ordering** in the first few years.
- Observation and measurement of **CPV** in the ν **sector.**
- Test of the **3-ν paradigm** (PMNS unitarity).
- Observatory for **astrophysical ν sources** (solar, atmospheric, SN).
- Search for **physics Beyond Standard Model** with and without **νs**



DUNE / LBNF / PIP-II: three interconnected efforts



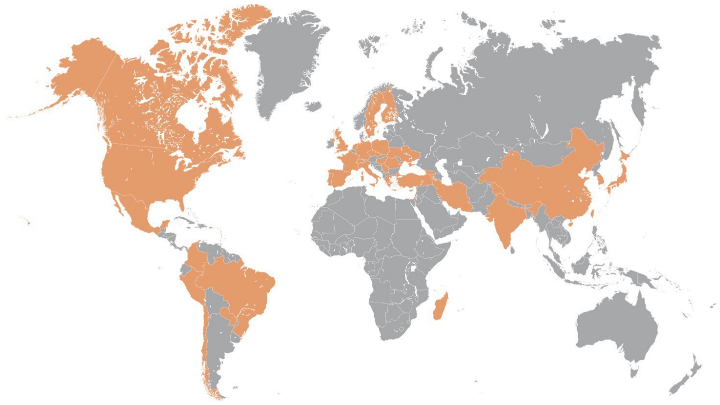
DUNE The **International Collaboration** to design, construct, and operate suites of Near and Far Detectors, and to plan and deliver a unique science program. → US (DOE), CERN, and more than 35 countries.

LBNF The **Long Baseline Neutrino Facility,** comprising the **Far and Near Sites** (**excavation**, **buildings**, **infrastructure**) and the **neutrino beam line**. → US (DOE), CERN, Switzerland, Brazil, Poland.

PIP-II The improvement plan for the Fermilab accelerator complex to provide the proton beam for DUNE, and to enable future programs at Fermilab. → US (DOE), India, Italy, UK, France, Poland.

Funded by:

DUNE: an International Collaboration



- 1,450 collaborators
- 215 Institutes, including CERN
- 35 countries

A long timeline already

- 2012: LAr TPC technology choice; large θ_{13}; LBNE reconfiguration (10 kt on surface).
- 2013: **European Strategy Update.**
- 2014:
  - **1st P5 Report;**
  - ICFA European Neutrino Meeting (APC, Paris);
  - LBNO-LBNE high level contacts; planning for Single Phase prototype at CERN;
  - Nigel Lockyer calls Neutrino Summit (July), launching new collaboration formation;
  - **CERN Neutrino Platform** official commencement.
- 2015: **DUNE** formed and named; **DOE-CERN agreement** for neutrino experiments.
- 2021: **Excavation** at Sanford Far sight **begins**
- 2023, Nov. 17th: signature of **international agreement for DUNE construction.**
- **2023: 2nd P5 report reaffirms support to DUNE, including Phase 2**
- Oct. January 31st, 2024: Far site **excavation completed !!**

P5 2014

Recommendation 12: In collaboration with international partners, develop a coherent short- and long-baseline neutrino program hosted at Fermilab.

(kt) of liquid argon (LAr) and a suitable near detector. **The minimum requirements to proceed are the identified capability to reach an exposure of at least 120 kt*MW*yr by the 2035 timeframe, the far detector situated underground with cavern space for expansion to at least 40 kt LAr fiducial volume, and 1.2 MW beam power upgradable to multi-megawatt power. The experiment should have the demonstrated capability to search for supernova (SN) bursts and for proton decay, providing a significant improvement in discovery sensitivity over current searches for the proton lifetime.**

European Strategy

CERN should develop a neutrino programme to pave the way for a substantial European role in future long base line experiments. Europe should explore the possibility of major participation in leading long-baseline neutrino projects in the US and Japan.

DUNE/LBNF/PIP-II status and plans in a nutshell

- LBNF is being **delivered in its entirety.**
  - Halls adequate for 4 modules and neutrino beam line upgradable to 2.4 MW

- The full program to be deployed in **two phases:**

  - **DUNE Phase I:**
    - FD (approved): 2 x 17 kt (total) LAr TPCs: one Horizontal Drift, one Vertical Drift.
    - ND (baseline TBC and approved by 2025): NDLAr with TMS; DUNE-PRISM; SAND on-axis.
  - PIP II: ongoing construction, first beam in 2031, reaching 1.2 MW by end 2032.
  - Fermilab plan: ACE: MIRT, Booster Replacement. Can provide up to **2.1 MW at DUNE start.**

DATES

  - **DUNE Phase 2,** as endorsed by P5 in December 2023

    Re-envisioned second phase of DUNE with an early implementation of an enhanced 2.1 MW beam—ACE-MIRT—a third far detector, and an upgraded near-detector complex as the definitive long-baseline neutrino oscillation experiment of its kind (section 3.1).

    - **DUNE ND plan:** More Capable Near Detector (HPGAr TPC, magnet, calorimeter).
    - **DUNE FD plan:** FD3 (vertical drift), FD4 (so called “opportunity module”, to be defined)

DATES

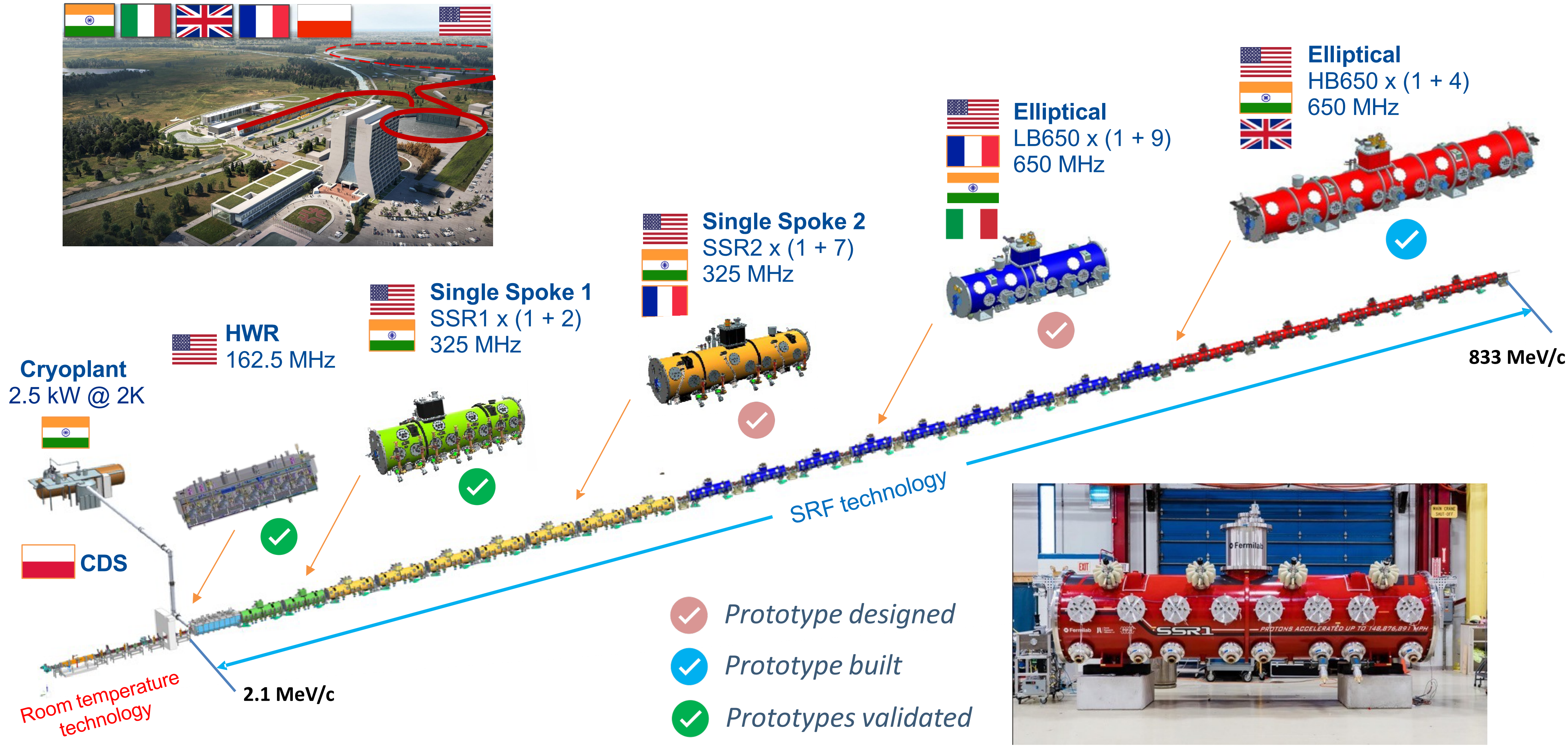
PIP-II

- New proton source for Fermilab : 800 MeV H– SRF linac.
- 1.2 MW protons, upgradable to multi-MW, CW-compatible.
- Linac to Booster transfer line.
- Accelerator Complex upgrades.

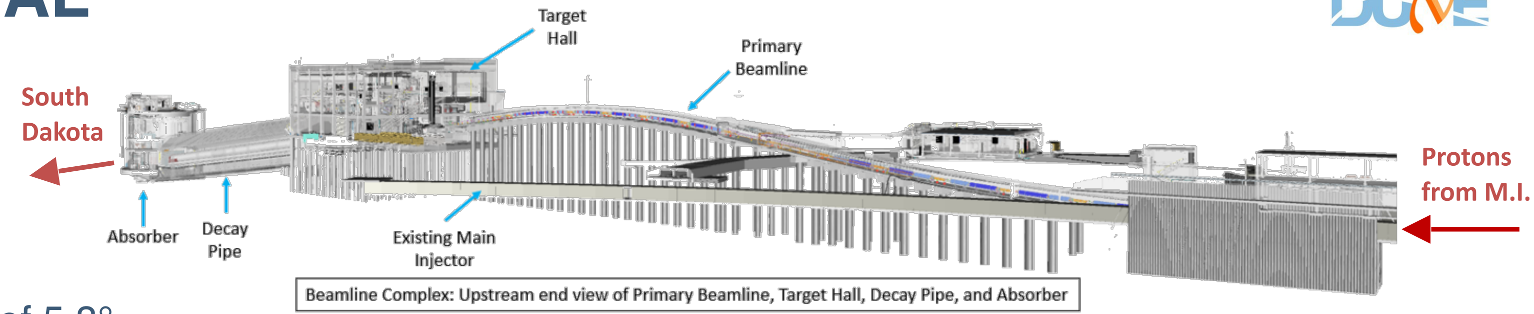
Beam Schedule

- Fermilab beams stop end 2026
- Beam commissioning: 2029-30
- Beam to DUNE: Fall 2031 ~ 1 MW 1.2 MW by end 2032 (maybe more with ACE/MIRT)

A key element: the high intensity SRF cryogenic Linac

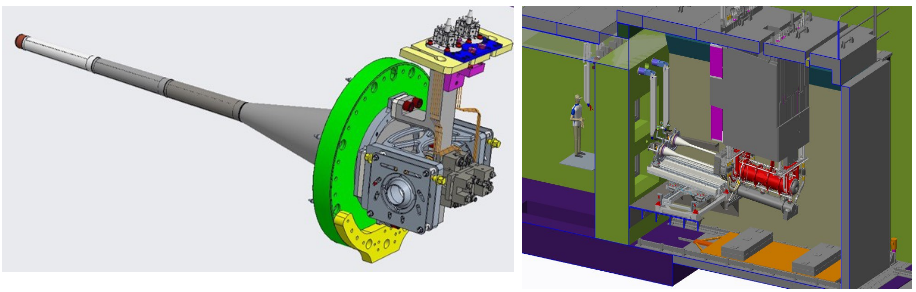


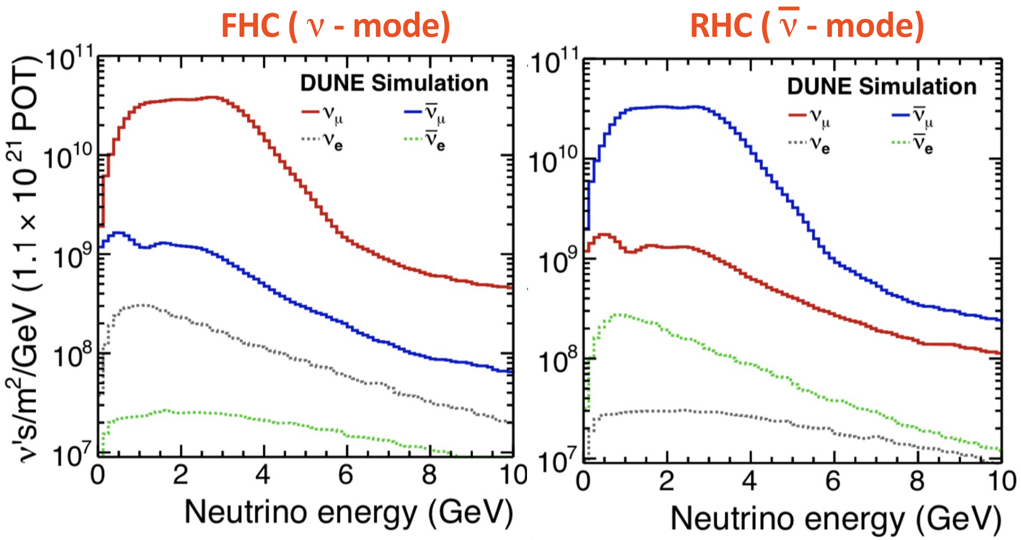
The ν beam at FNAL



- Neutrino beam line at a slope of 5.8°
- Primary proton beam (60-120 GeV) on a graphite target **(1.1–1.9)10²¹ pot/yr**
- Horns/beam line designed to maximise CP violation sensitivity
- Pulse duration: 10 µs. Repetition period: 1.33 s (possibly to be reduced down to **0.7 s by ACE/MIRT**)
- Forward/Reverse Horn Current (FHC/RHC) ν / $\bar{\nu}$ enhanced
- **Wide band beam ~ 1-6 GeV**

Target design and remote handling (UK)





Eur. Phys. J. C **80** 10, 978 (2020)

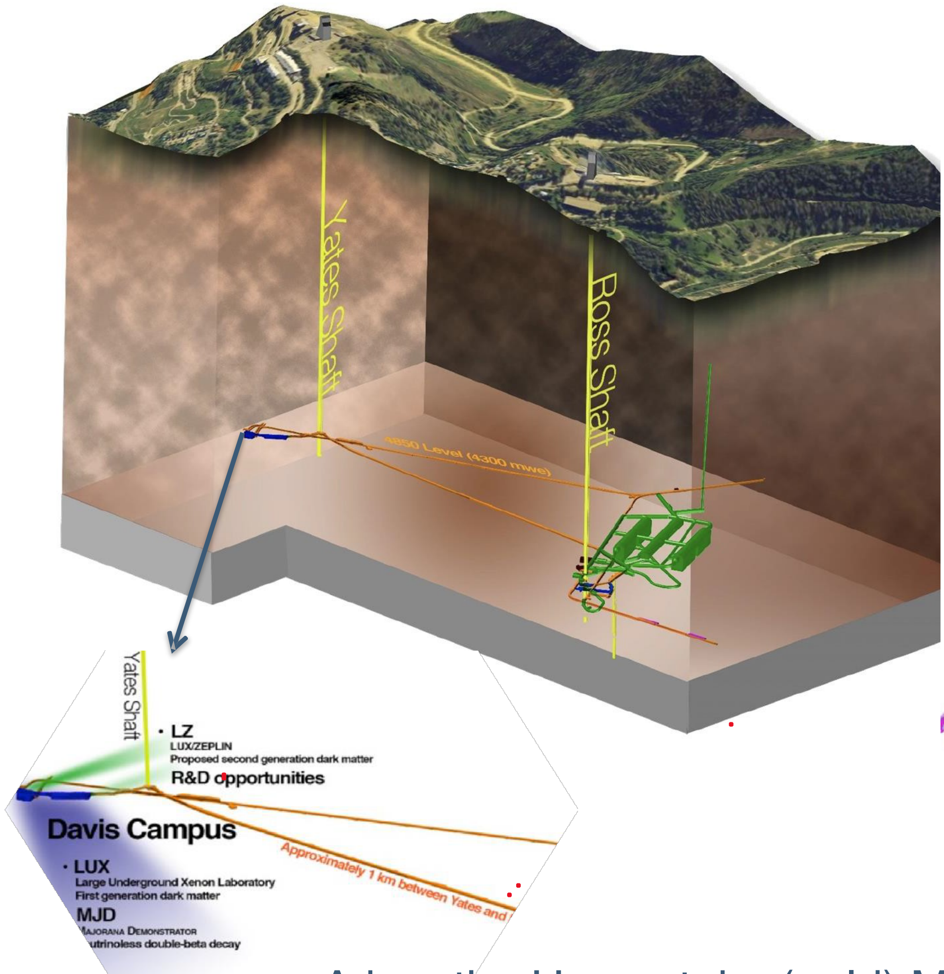
Accelerator Complex Evolution (ACE)

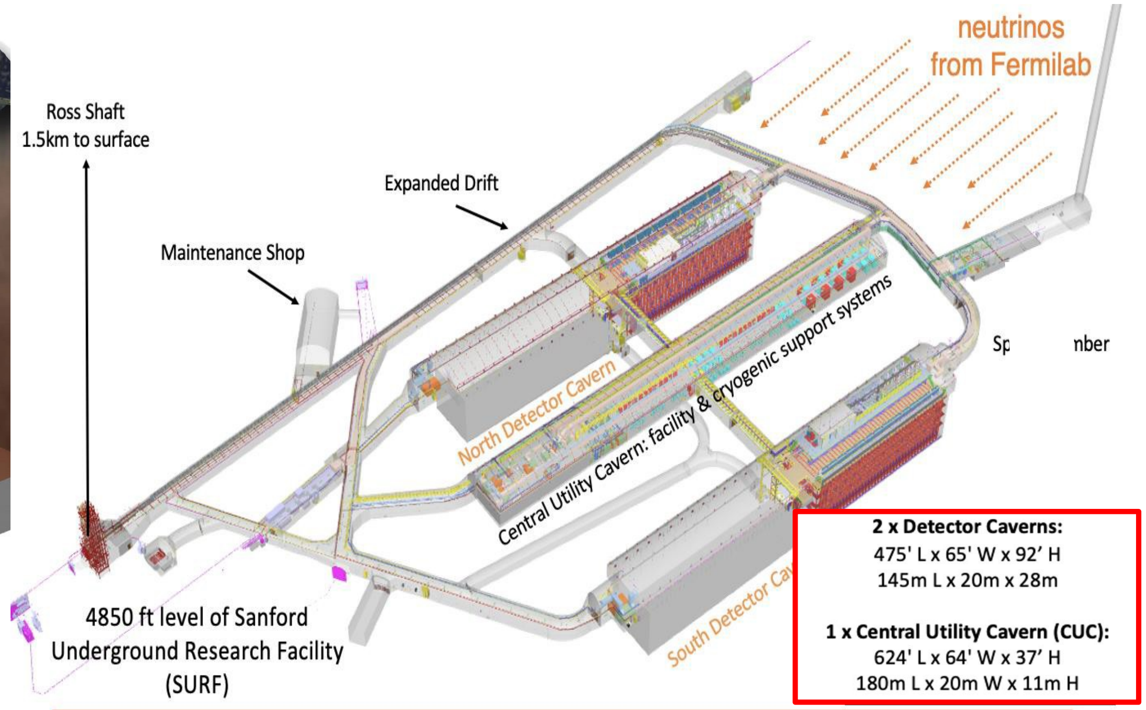
- ACE was proposed by Fermilab and endorsed by P5. It has two distinct steps:

- **MIRT**, the **M**ain **I**njector **R**amp and **T**argets:
  - Shortens MI cycle time with faster ramp time (**now 1.33 s**, PIP-II 1.2 s, **MIRT 0.7 s**).
  - Brings max. MI power from **1.2 MW** to **2.14 MW.**
  - Requires enhancements of the acceleration and magnet systems in the MI.
  - Must be accompanied by additional measures to improve Booster reliability.
  - Requires development of **new target** (and first horn) for higher power, faster pulsing.
  - It could allow to run DUNE with **2.1 MW in 2032.**

- **Booster Replacement:** it is proposed that a project is established to *develop and deliver a Booster replacement accelerator.* This will be **Fermilab future infrastructure,** and also provide **2.4 MW to DUNE** in parallel to other programs.

Sanford Underground Research Facilities





A.k.a. the Homestake (gold) Mine in the Black Hills (Ray Davis ^{37}Cl ν experiment site)

Excavation 100% completed on Jan. 31st, 2024!

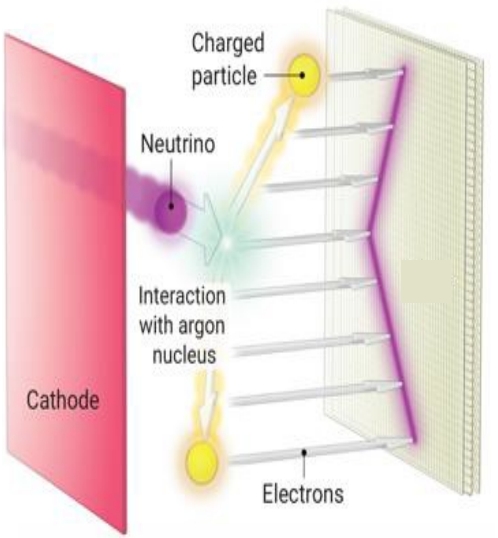
East end scaffolding progress
in South Cavern

Central Utility Cavern

Concrete work underway
in North Cavern

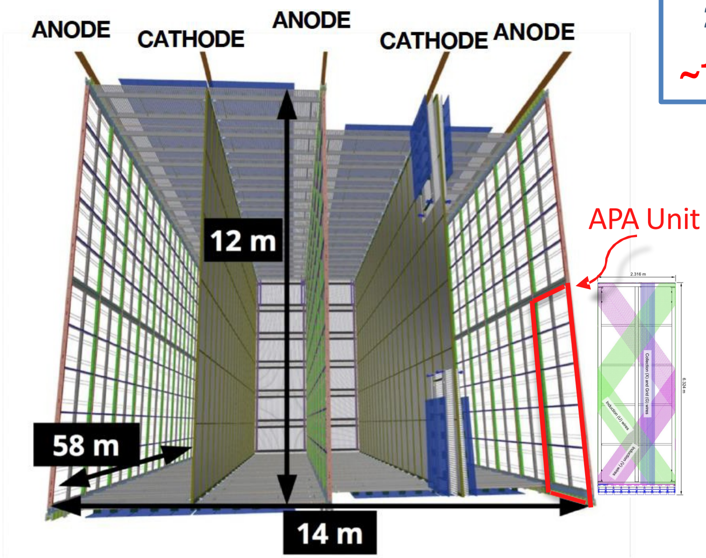
DUNE - Far Detector Modules 1&2

LAr TPC technology



Liquid Argon TPC (C. Rubbia, 1977) is the technique with the best particle imaging capability at kton scale:

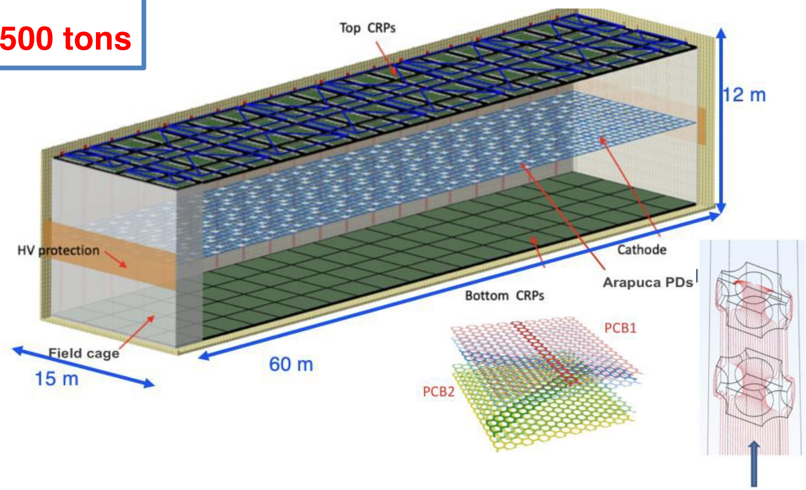
FD1-HD «Horizontal drift» (ICARUS concept, wires)



- 150 Anode Plane Assemblies (APAs)
- 384,000 readout wires
- Anode-Cathode 3.5 m drift;
- 500 V/cm field; cathode at -180 kV;
- 6000 photon detection system (PDS) channels
- PDS X-Arapuca modules embedded in APA

BOTH:
28'500 m3
~17'500 tons

FD2-VD «Vertical drift» (Simpler, no wires)

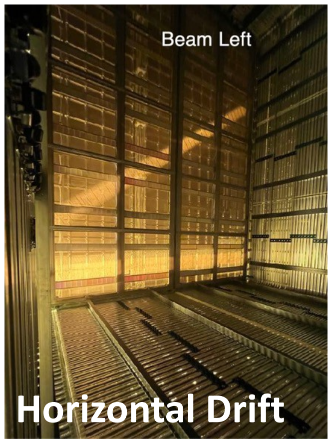


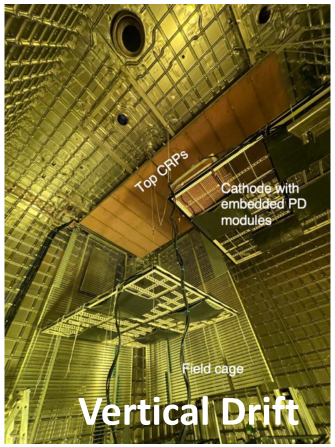
- Charge Readout Planes : perforated PCB's with segmented electrodes (strips)
- CRPs at the top and bottom
- Cathode (-300 kV) in the middle
- two 6.5 m drift chambers 450 V/cm field
- X-Arapuca modules integrated on cathode and on cryostat walls.

Cryostats and prototypes at CERN Neutrino Platform

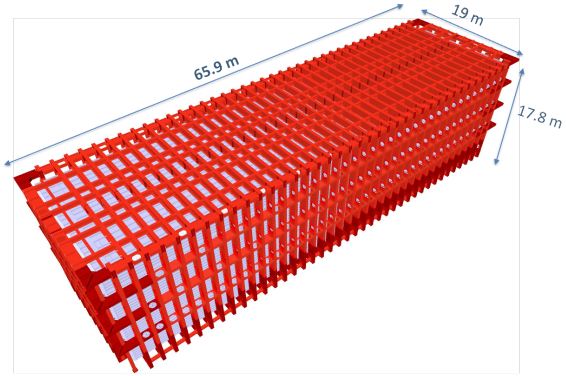
- **Horizontal** and **Vertical** drift technologies **successfully tested and validated at CERN NP**

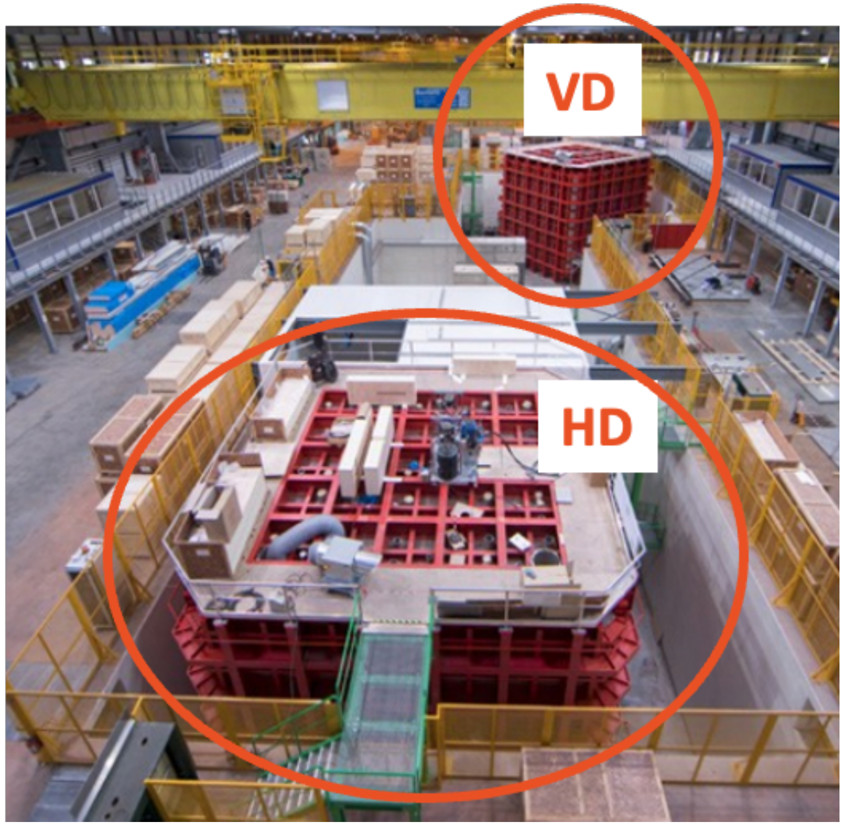
- 2 mostly identical cryostats, 700 ton LAr each on 2 dedicated beamlines
- **HD TPC:**
  - 410 tons active volume (ICARUS 475)
  - 3.6 m drift (MicroBooNE 2.6)
- **VD TPC:** 300 kV across 6 m drift stable over long periods



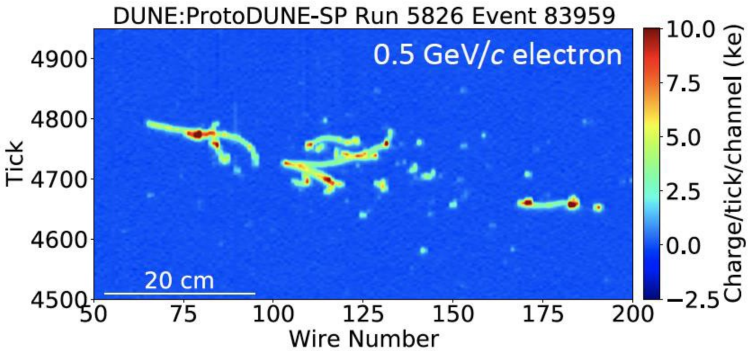


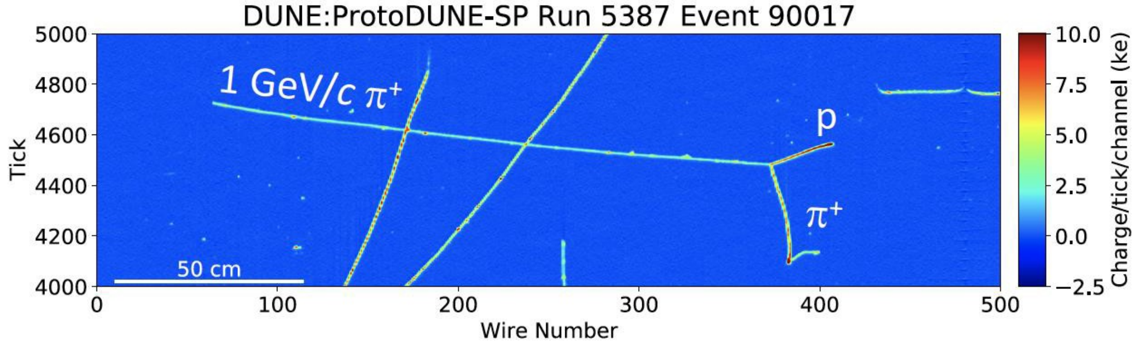
Same drift lengths and fields as in DUNE full detectors

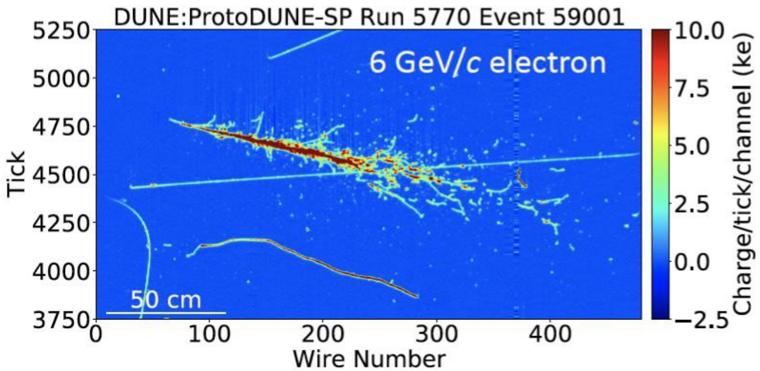




Horizontal drift performance - Run 1







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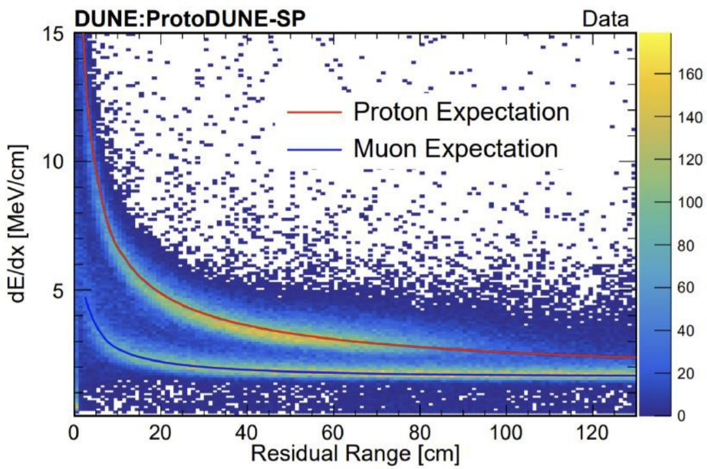
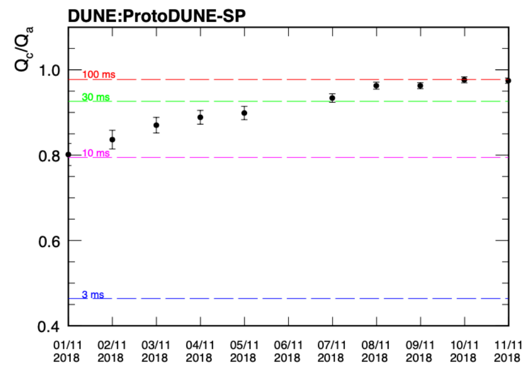




JINST, P12004 (2020)

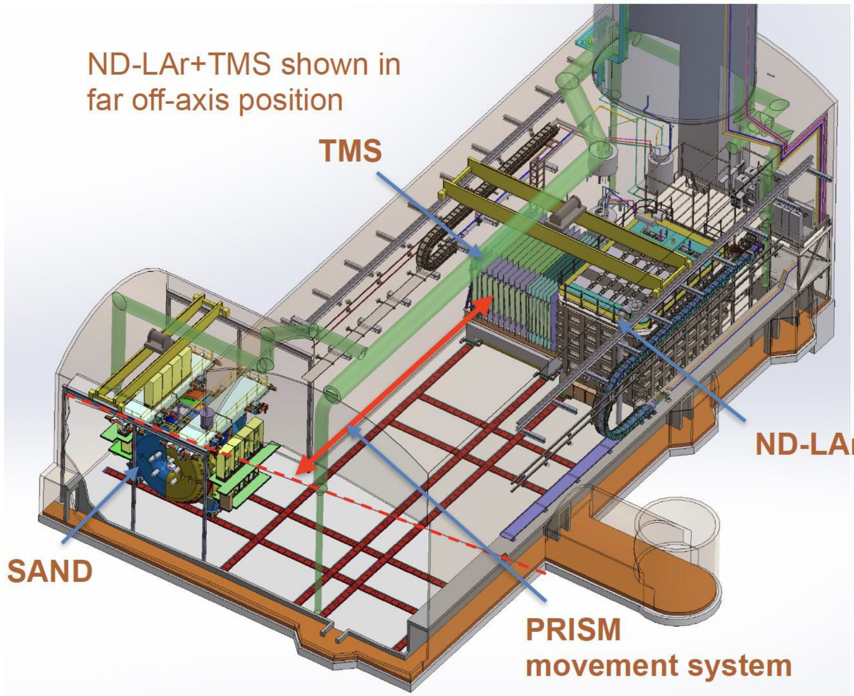
Protodune phase 2 under way both for HD and VD - A physics program is included.

Near Detector

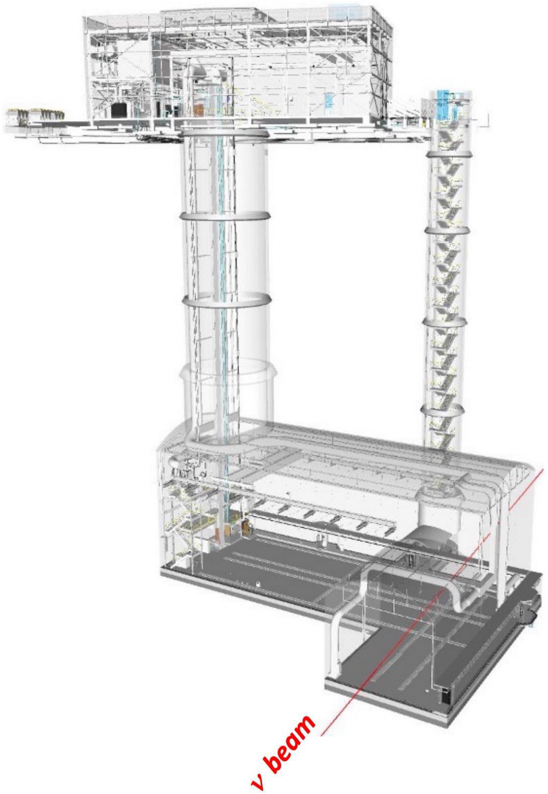
$$\frac{\frac{dN^{far}_{\nu_e}}{dE_{rec}}}{\frac{dN^{near}_{\nu_\mu}}{dE_{rec}}} = \frac{\int P_{\nu_\mu \to \nu_e}(E_\nu) * \phi^{near}_{\nu_\mu}(E_\nu) * F_{far/near}(E_\nu) * \sigma^{Ar}_{\nu_e}(E_\nu) * D^{far}_{\nu_e}(E_\nu, E_{rec})\ dE_\nu}{\int \phi^{near}_{\nu_\mu}(E_\nu) * \sigma^{Ar}_{\nu_\mu}(E_\nu) * D^{near}_{\nu_\mu}(E_\nu, E_{rec})\ dE_\nu}$$

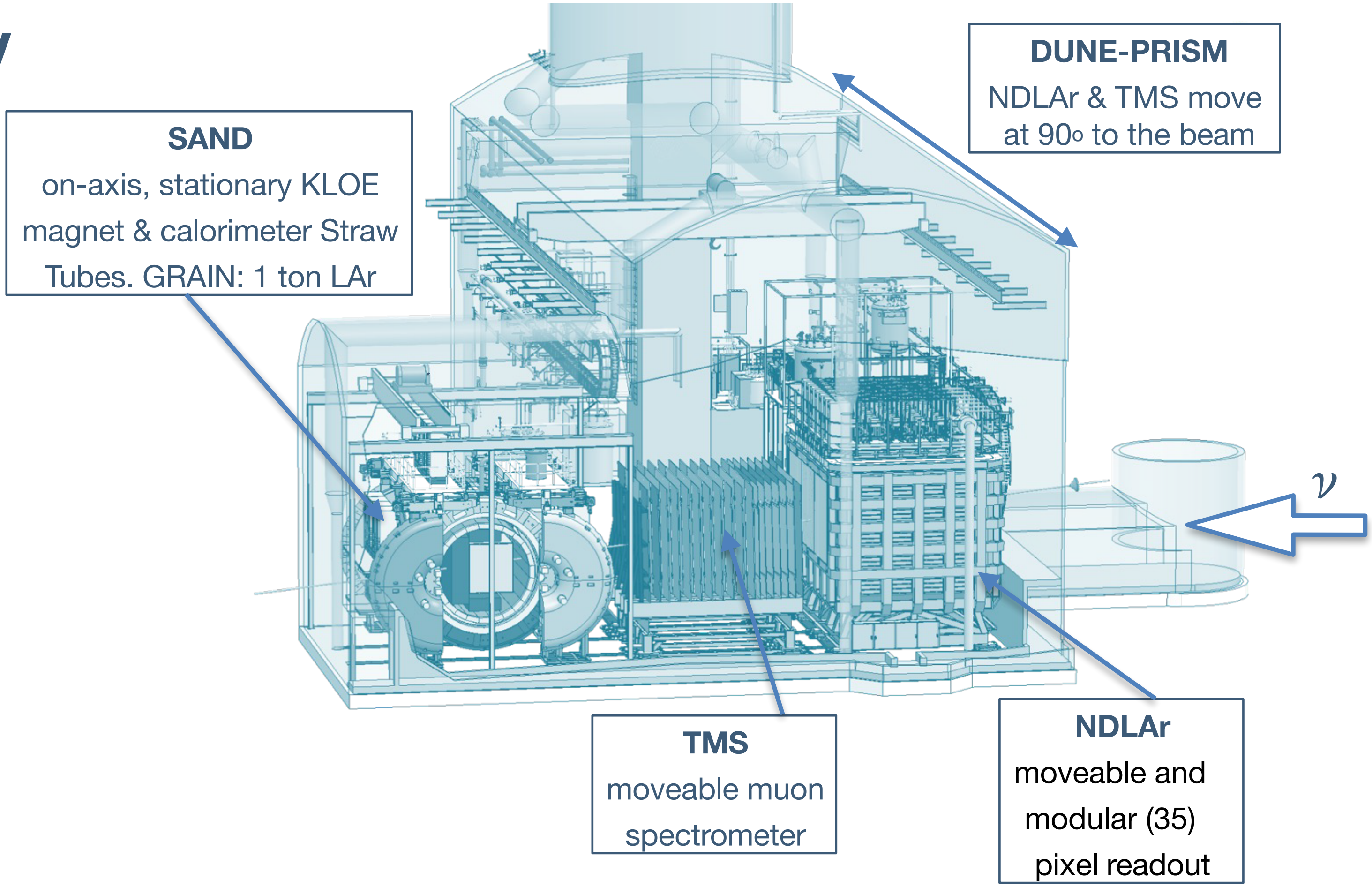
- Neutrino beam **rate** and **spectrum** to **predict un-oscillated event rates in the FD**
- Constrains **flux**, **cross sections** and **detector response** for **oscillation measurements** and monitor **beam stability**
- Additional physics program on neutrino physics and BSM

- Configuration (Phase I):
  - **ND-LAr:** 7x5 array 1x1x3 m³ LArTPCs with pixel readout
  - **TMS:** Magnetised steel range stack for muon momentum and sign from ν_μ CC interactions in ND-LAr
  - **DUNE-Prism:** movable system for ND-LAr+TMS up to 28.5 m off-axis (ANGOLO!)
  - **SAND:** On-axis magnetised detector with LAr target (GRAIN), tracking (STT) and calorimeter (ECAL)



Near Detector Facility





- ND Hall **574 m from target**
- 60 m underground with “small” artificial hill for further radiation shield on surface
- **Beneficial occupancy: 2028**
- **Ready for beam: 2032**

Experimental Strategy for oscillations

$$P(\nu_\mu \to \nu_e) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\left(\frac{\Delta m^2}{a-\Delta m^2}\right)\sin^2\left(\frac{a-\Delta m^2}{4E}L\right) + \sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\left(\frac{\delta m^2}{a}\right)\left(\frac{\Delta m^2}{a-\Delta m^2}\right)\sin\left(\frac{aL}{4E}\right)\sin\left(\frac{a-\Delta m^2}{4E}L\right)\cos\left(\frac{\Delta m^2 L}{4E}\right)\cos\delta \; +$$

$$+\cos^2\theta_{13}\sin^2 2\theta_{12}\left(\frac{\delta m^2}{a}\right)^2\sin^2\left(\frac{aL}{4E}\right) - \sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\left(\frac{\delta m^2}{a}\right)\left(\frac{\Delta m^2}{a-\Delta m^2}\right)\sin\left(\frac{aL}{4E}\right)\sin\left(\frac{a-\Delta m^2}{4E}L\right)\cos\left(\frac{\Delta m^2 L}{4E}\right)\sin\delta$$

$\overline{\nu}_\mu \to \overline{\nu}_e$

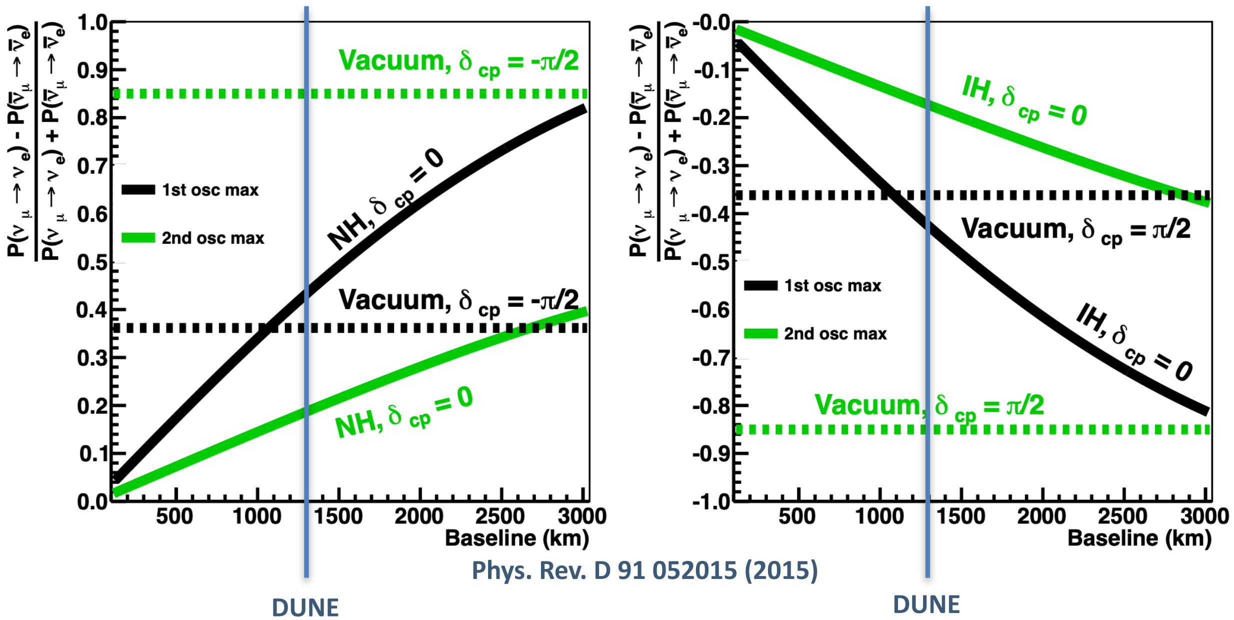
$a \to -a$

$\delta \to -\delta$

Leading order approximation

$$\mathcal{A}_{cp}(E_\nu) = \left[\frac{\mathrm{P}(\nu_\mu \to \nu_e) - \mathrm{P}(\bar{\nu}_\mu \to \bar{\nu}_e)}{\mathrm{P}(\nu_\mu \to \nu_e) + \mathrm{P}(\bar{\nu}_\mu \to \bar{\nu}_e)}\right] \approx \frac{\cos\theta_{23}\sin 2\theta_{12}\sin\delta_{CP}}{\sin\theta_{23}\sin\theta_{13}}\left(\frac{\Delta m^2_{21} L}{4E_\nu}\right) + \text{ matter effects.}$$

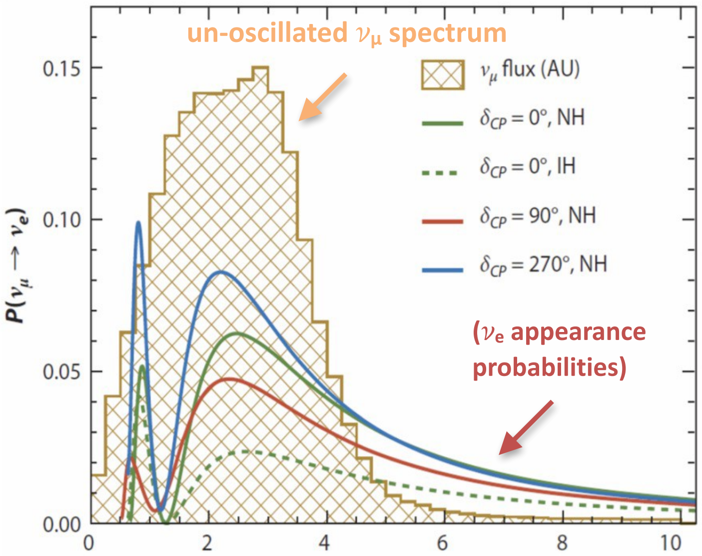
- Long baseline + wide-band beam: **unfold CPV and matter effects** using information from the **first** and **second oscillation maxima**
  - Baseline ~ 1300 km
    - 1st peak at ~ 2.6 GeV
    - 2nd peak at ~ 0.65 GeV



Phys. Rev. D 91 052015 (2015)

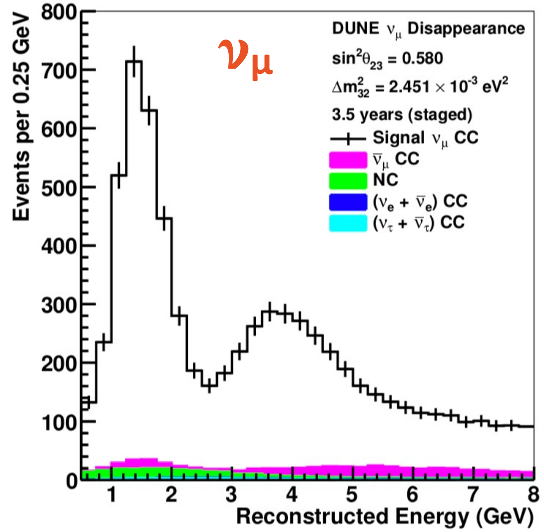
DUNE Oscillation physics

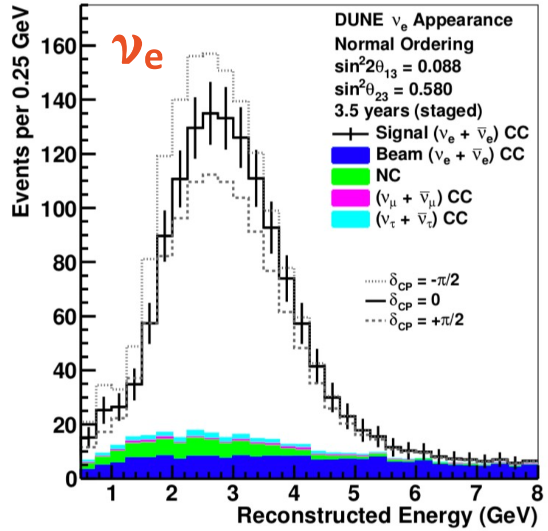
DUNE Collaboration, Eur. J. Phys. C80, 978 (2020)



ν_μ disappearance

$\nu_\mu \rightarrow \nu_e$ appearance





In year 1 alone, DUNE will collect ~150 oscillated ν_e events. This is approx. the sum of T2K + NOvA

- *assuming a beam ramp-up to 1.2 MW, 2 FDs, normal ordering, θ_{CP}=0*
- *expected range is 70-180 ν_e events in FHC, depending on true MO, CP*
- *a factor 1.75 more with ACE-MIRT*

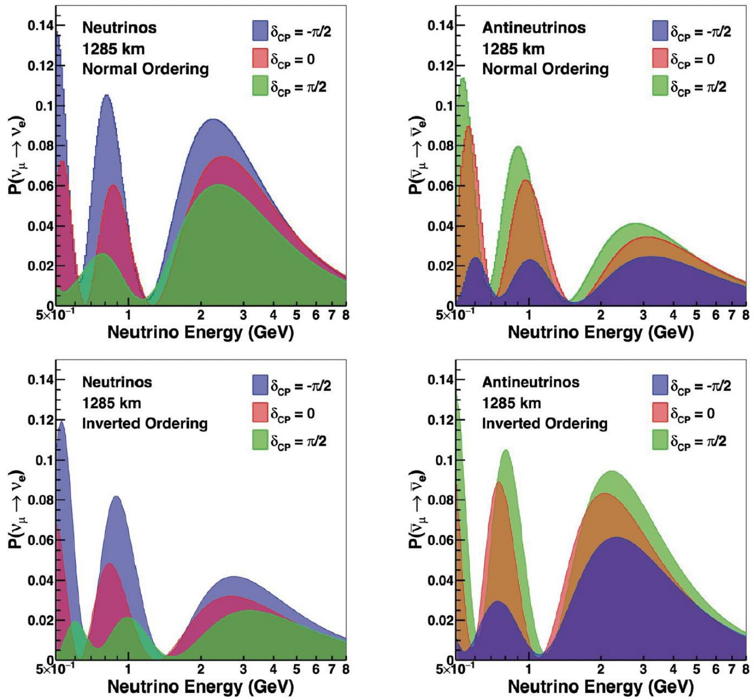
Oscillation shapes

- **Mass ordering** and **CPV** induce different shapes in oscillation probabilities of $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
- **DUNE's unique capability: wide band beam** covering several oscillation peaks measures these shapes over more than a full period, **disentangling degeneracies.** δ_{CP}**, M.O.** and θ_{23} **octant** with a single experiment.

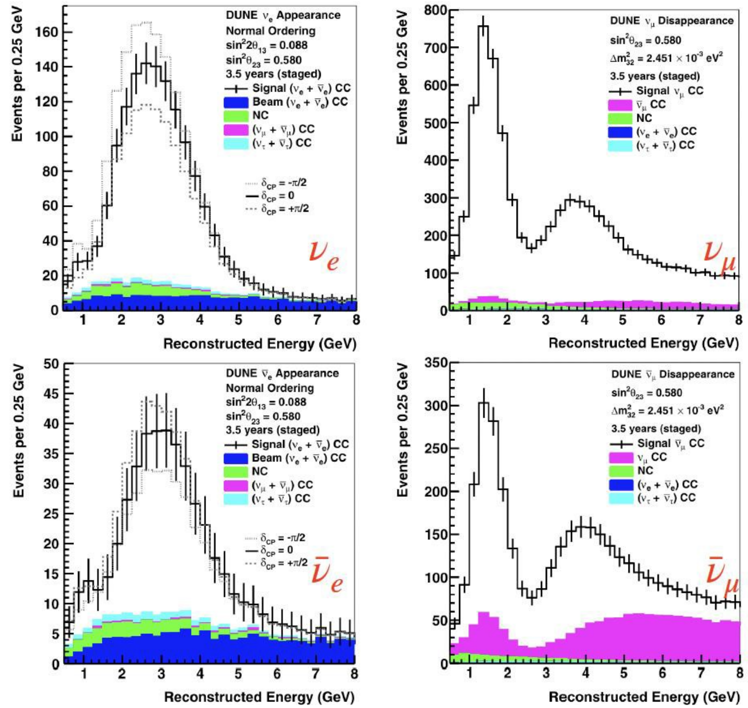
$\nu_\mu \rightarrow \nu_e$ $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

Normal Ordering

Inverted Ordering



$\nu_\mu \rightarrow \nu_e$ disappearance

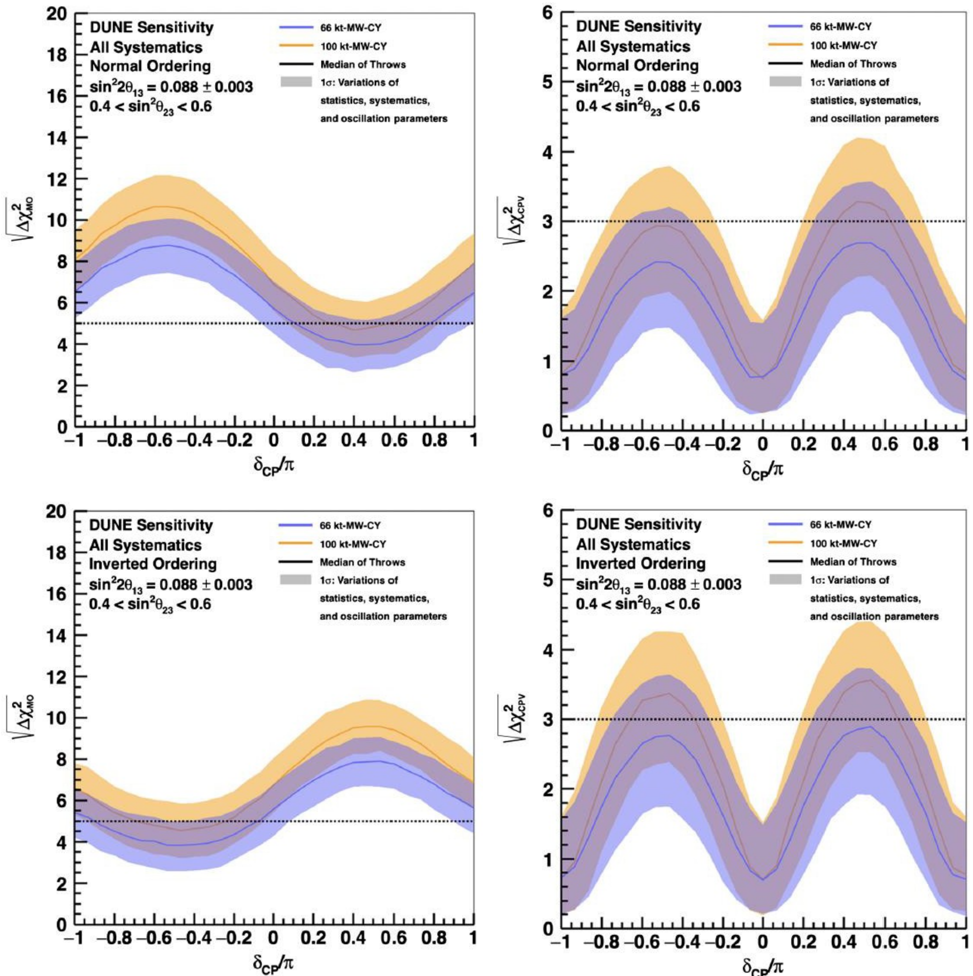


FHC
ν mode

RHC
$\bar{\nu}$ mode

Sensitivity to CPV - Phase I

- DUNE Phase-I will:
  - unambiguously resolve the neutrino mass ordering at **3σ** **(5σ)** level with a **66** **(100)** kt · MW · yr exposure
  - measure CPV at 3σ level with a **100 kt** · **MW** · **yr** exposure for the maximally CP-violating values $\delta_{CP} = \pm \pi/2$



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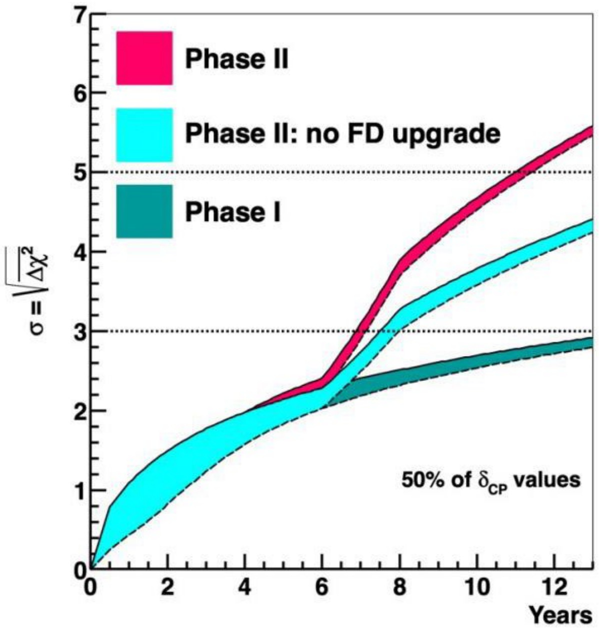
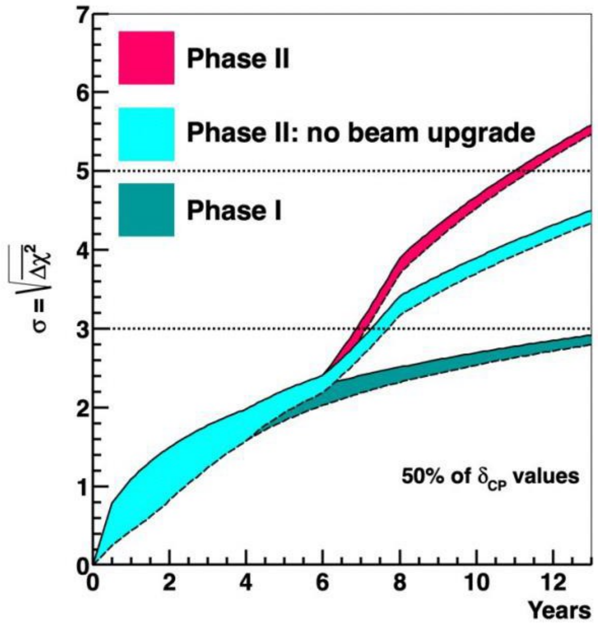
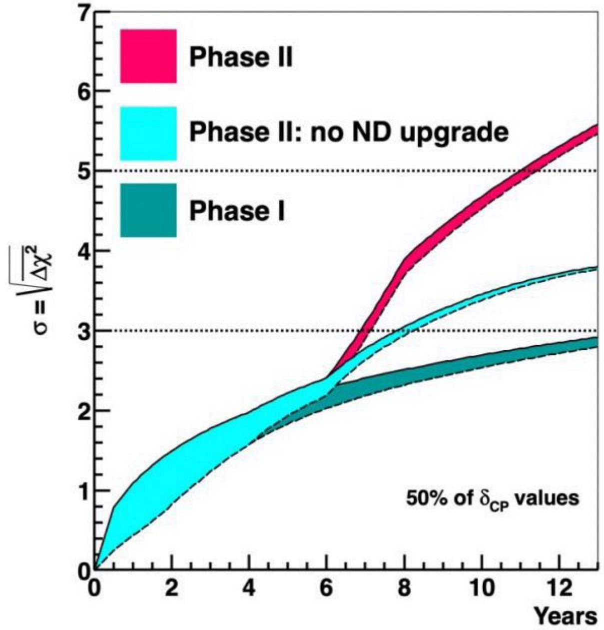
DUNE sensitivities at higher exposures (Phase II)

To achieve all P5 goals it is need : Detector Mass 40 kton (4 modules) + Beam power upgrade to 2.4MW + Improved Systematics (Near detector upgrade)







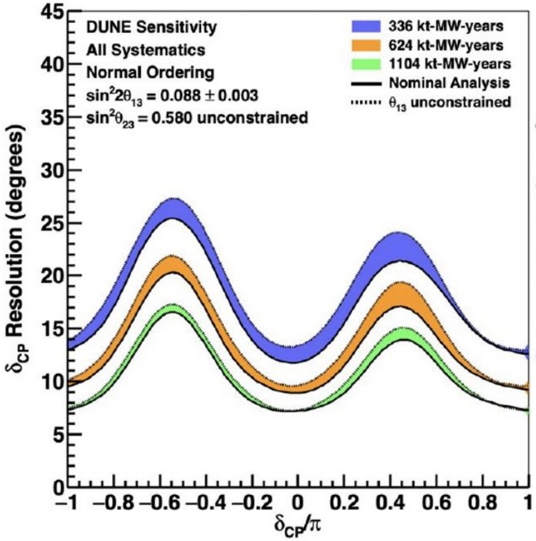
If $\delta_{CP} = \pm 90°$, CP violation at 3σ in Phase I

Phase II: If $\delta_{CP} = \pm 90°$ 5σ in 7 years
For 50% of δ_{CP} values 5σ CPV in 12 years

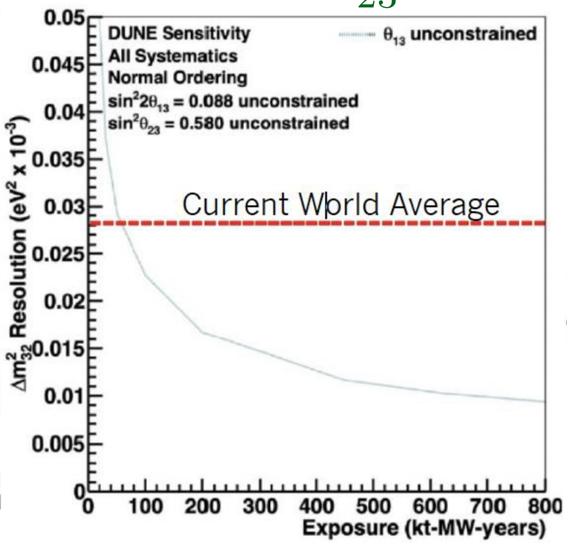
DUNE resolution

- DUNE can measure with high precision 4 oscillation parameters.

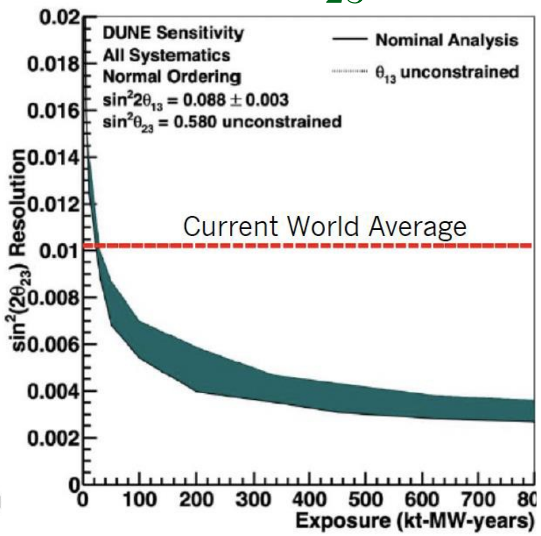
FINAL δ_{CP} **resolution 6° ÷16°**



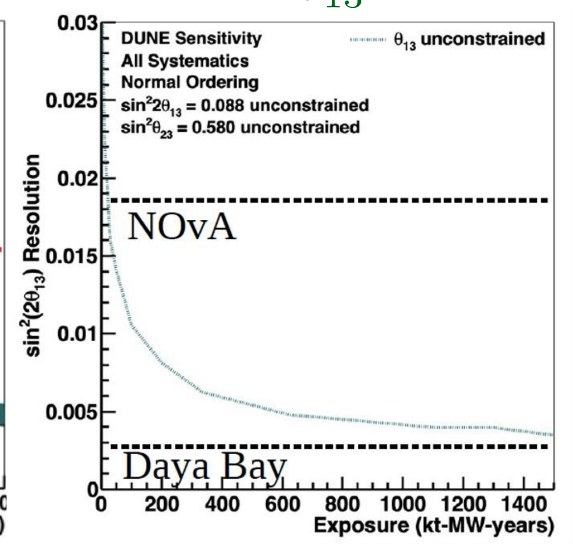
Δm^2_{23}



θ_{23}



θ_{13}



Search for Baryon Number Violation via proton decay

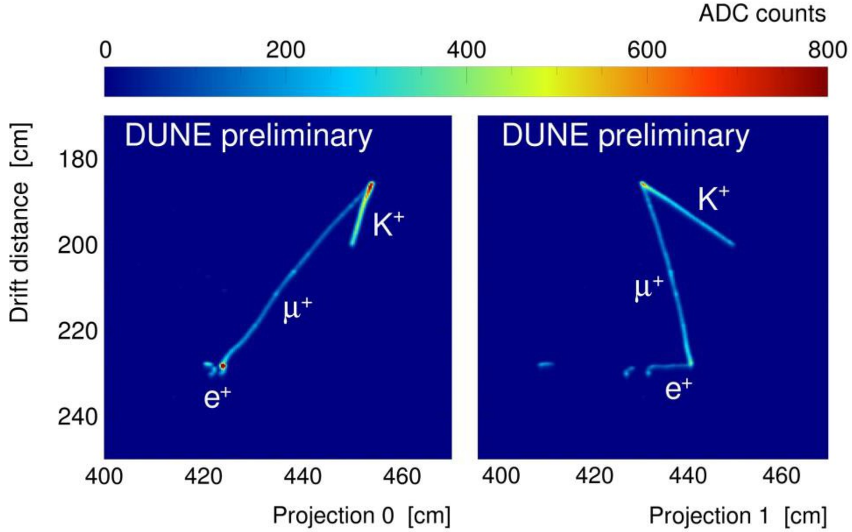
- The channel $p \longrightarrow K^{+}\bar{\nu}$ is dominant in many SUSY GUT models

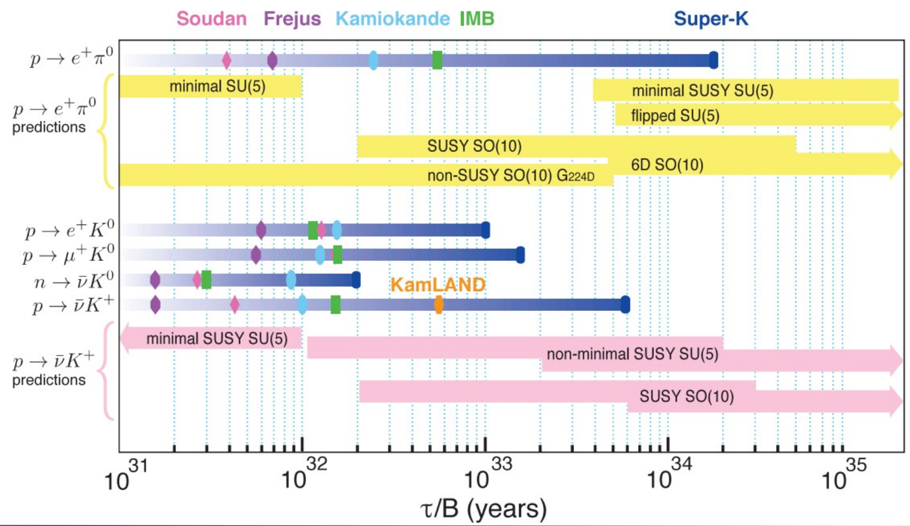
- **LArTPC technology** has the **unique capability** to observe the **entire decay chain** for proton decays into charged kaons
    - Identify isolated kaon by dE/dx and decay products

- Main **background**: **atmospheric neutrinos**

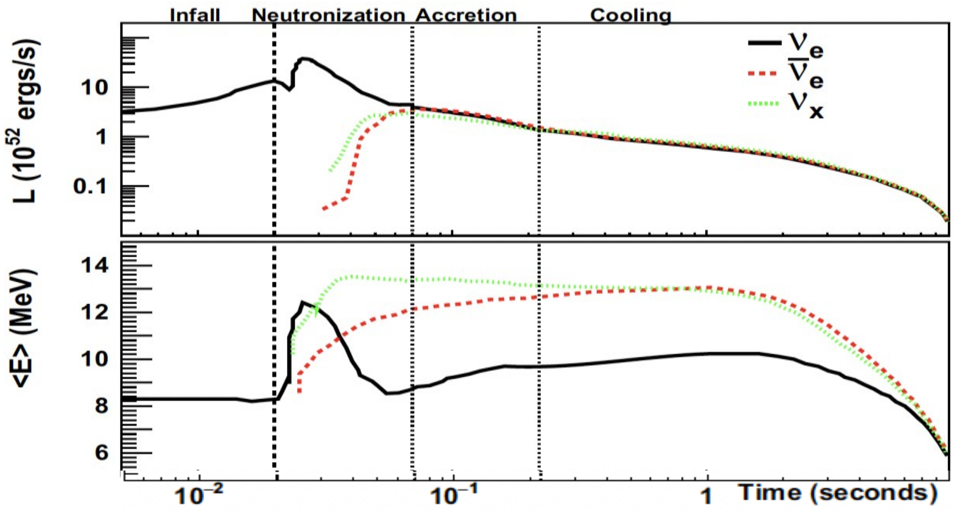
- BDT exploiting energy deposition topology and supported by CNN provides
    - Signal: 15% efficiency
    - Background: ~ 1 event / M kt-year

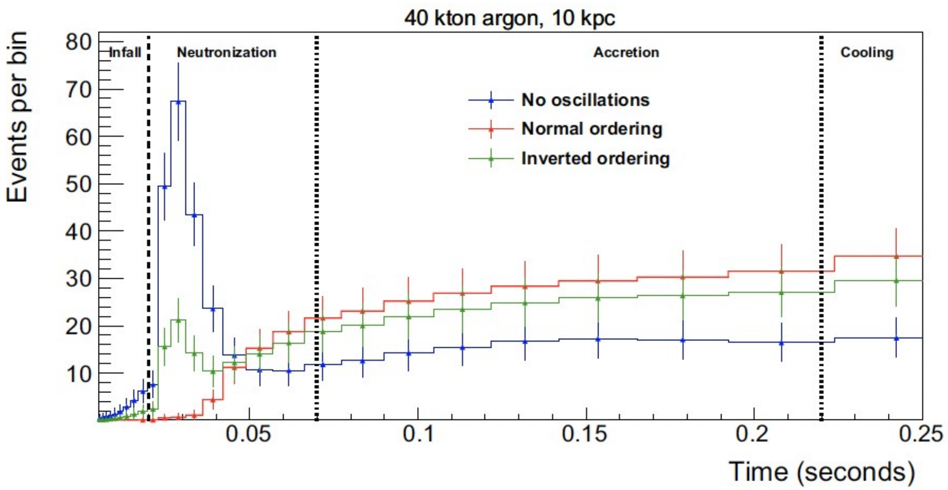
- Sensitivity:
    - Assuming no signal in 10 y, 40 kt FV and an improved 30% signal efficiency:
        - 1.3×10^{34} years (90% C.L.)





SN burst neutrinos





DUNE sensitive to ν_e CC events by

$\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$

exploiting the Ar target and to ν ES on electrons thanks to its large mass

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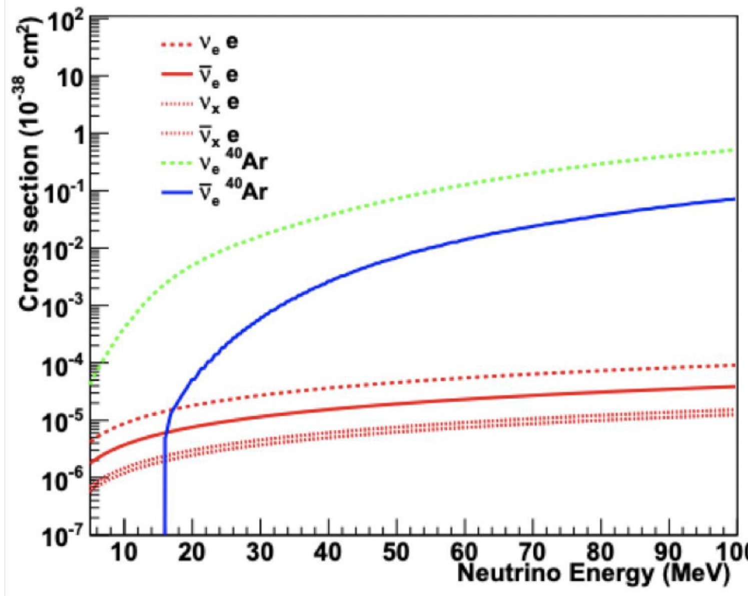


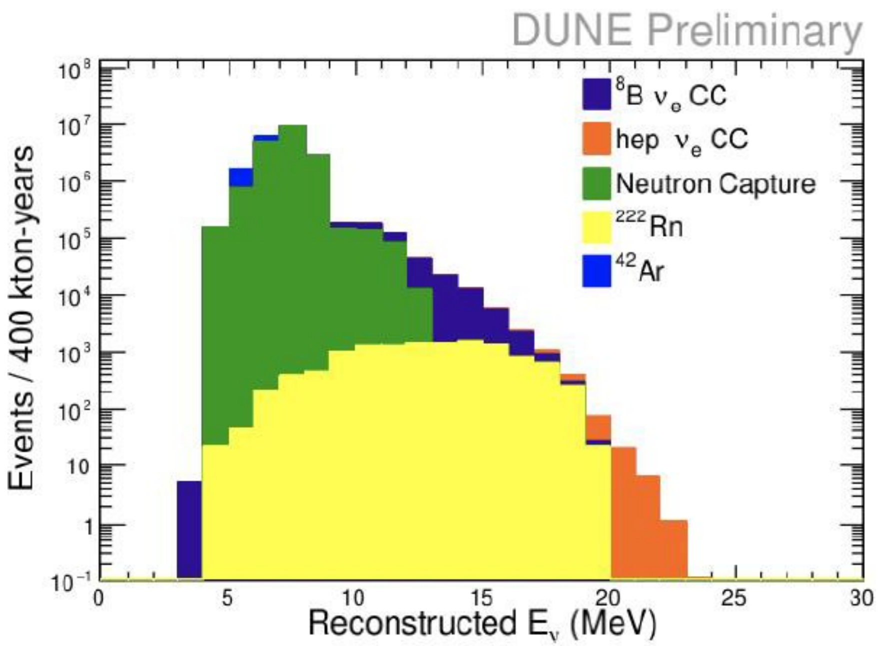
Solar neutrinos

$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$$

CC - electron neutrino only

$$\nu_{e,\mu,\tau} + e^- \rightarrow \nu_{e,\mu,\tau} + e^-$$

ES - all flavours, electron neutrino enhanced, flavour blind



(*) F. Capozzi et al PRL 123 (2019) 13

On-going work on solar neutrinos

Sensitive to ^{8}B and hep fluxes

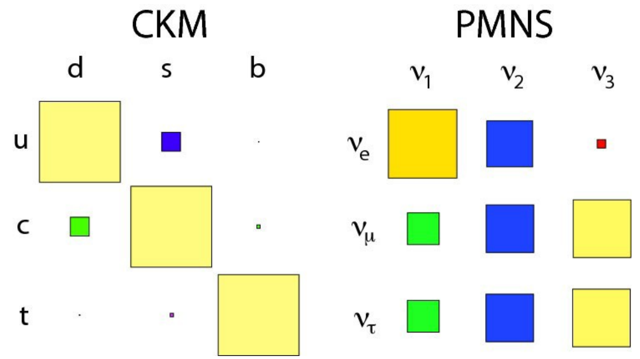
Measure oscillation parameters

Proposals for the 4th “opportunity” module to enhance the low energy physics programme

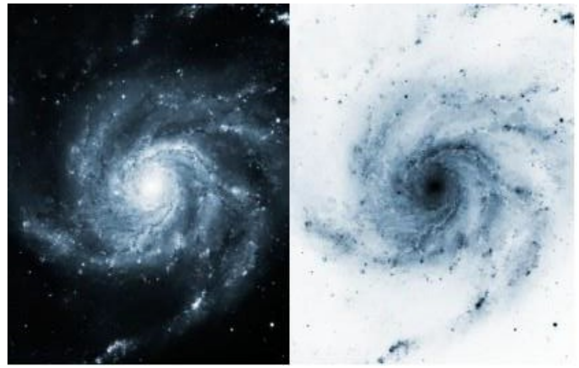
Thank you !

Fundamental Questions

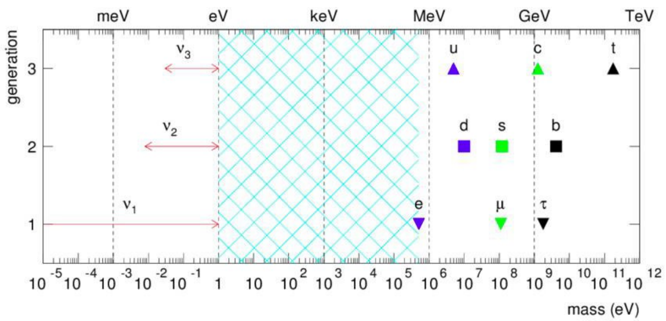
Can ν mixing teach us something about flavour ?
Are there underlying flavour symmetries ?



Is leptogenesis playing a role in BB matter-antimatter asymmetry ? Do protons decay ?



What is the origin of neutrino mass?
Why are the neutrinos so light?



Are there light sterile neutrinos?
Can non-unitary reveal new physics BSM ?

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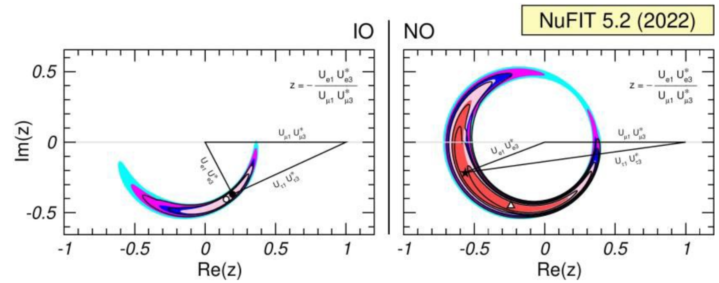


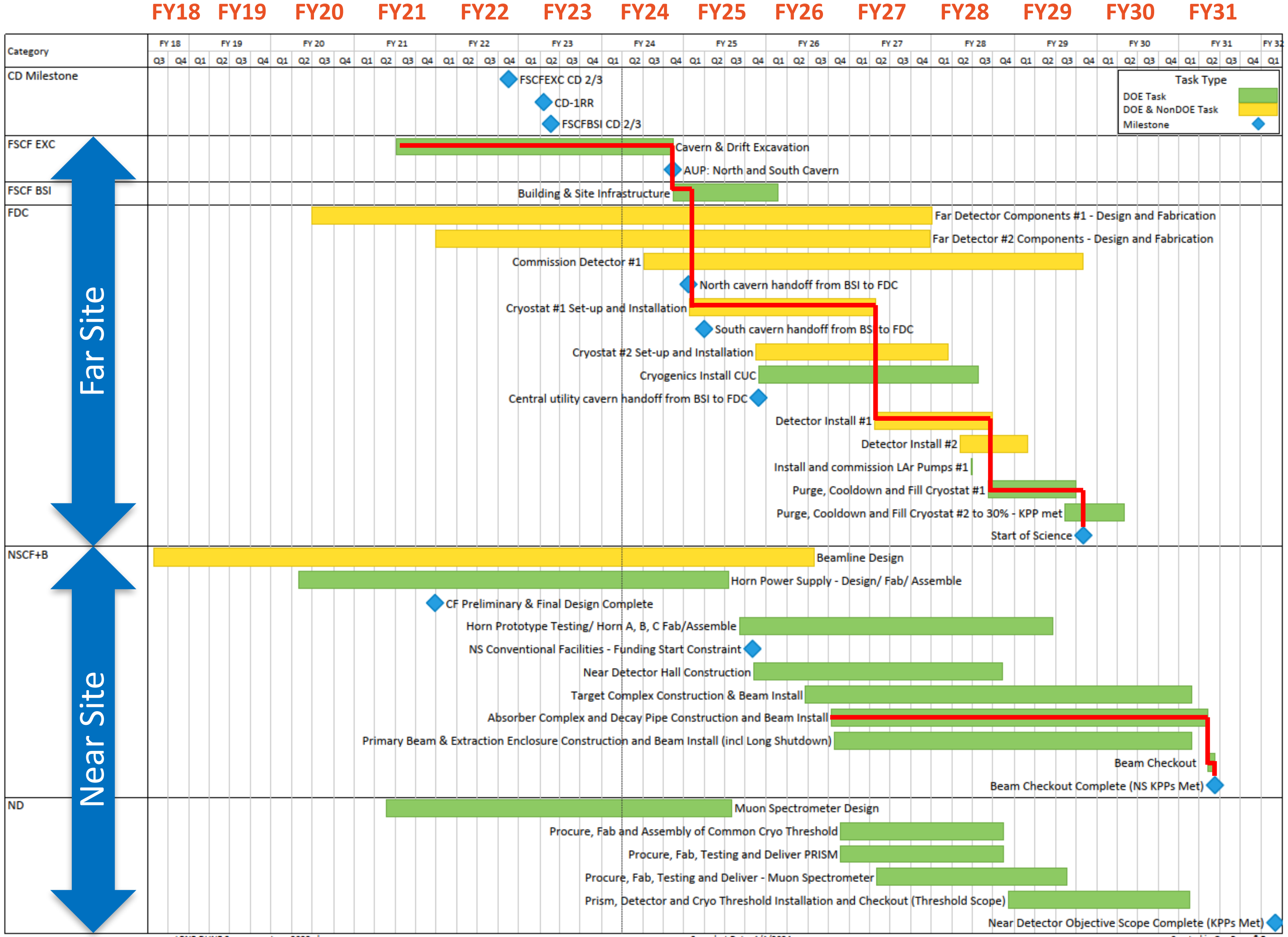
LBNF + DUNE Schedule

EXCAVATION

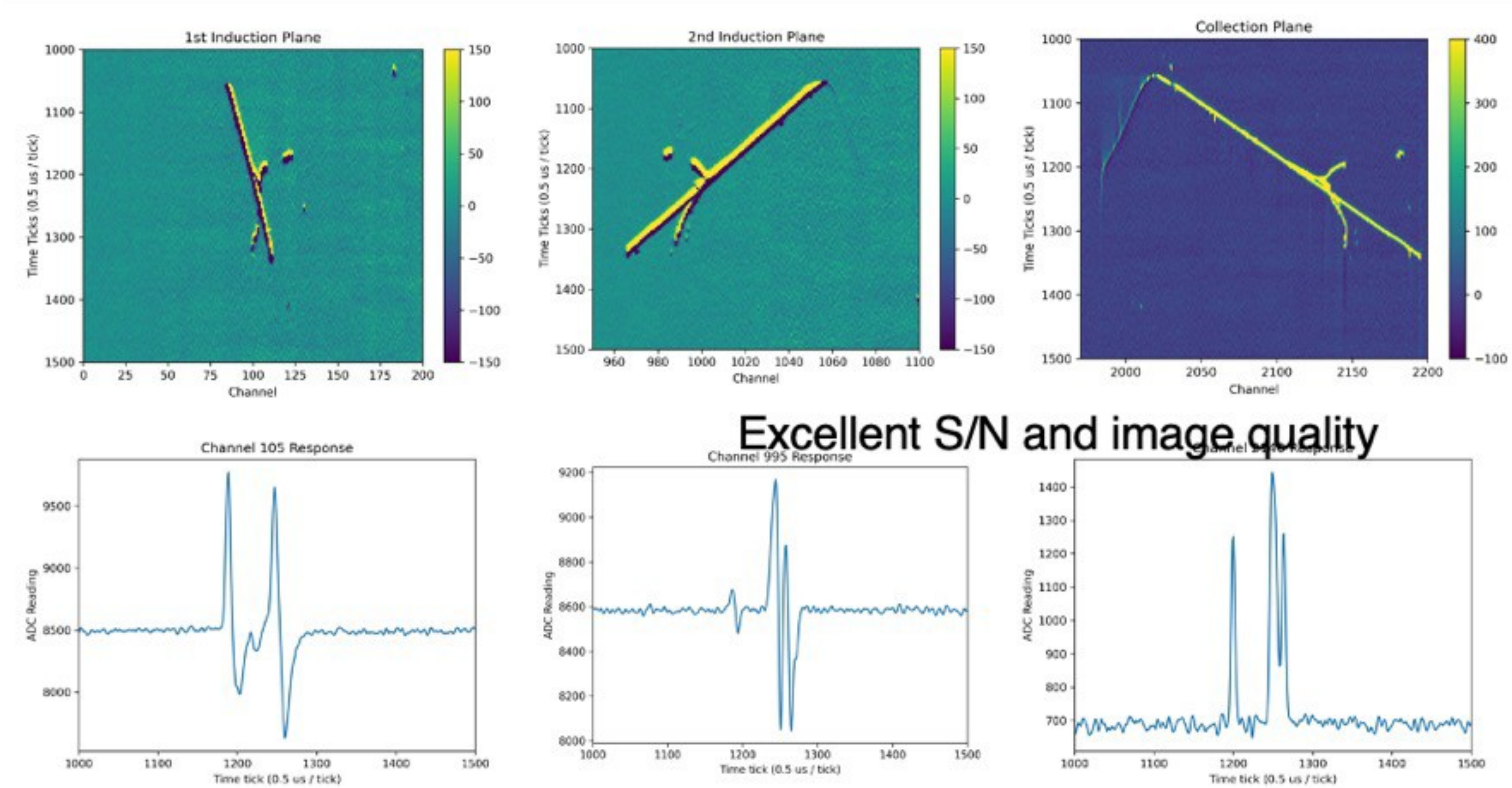
FAR DETECTORS (HD & VD) FABRICATION, INSTALLATION FILLING AND COMMISSIONING

HORNS, TARGET, DECAY TUNNEL, NEUTRINO BEAM, NEAR DETECTOR HALL

NEAR DETECTORS



Vertical drift Performance - prototypes



Excellent S/N and image quality